Recent PNT Improvements and Test Results Based on Low Earth Orbit Satellites

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BIOGRAPHIES

Dr. Gregory Gutt is the President and Chief Technology Officer of Satelles. As a graduate student, Greg developed ultra-low-noise superconducting sensors for NASA's Gravity Probe B program. Greg later went on to become a Boeing Technical Fellow and is the original inventor of the Satelles Time and Location technology.

Dr. David Lawrence is the Chief Navigation Architect for Satelles. In addition to authoring over 20 papers and over 30 patents, Dr. Lawrence has developed high performance navigation software that has been deployed in aircraft landing, precision agriculture, mining, transportation, and machine automation.

Dr. Stewart Cobb is the Chief Hardware Architect for Satelles. Dr. Cobb invented and developed the first commercial pseudolites. He led the development of five generations of GNSS receivers, four generations of GNSS pseudolites, and three generations of STL receivers. He holds at least 18 patents related to satellite navigation.

Dr. Michael O'Connor is the Chief Executive Officer of Satelles. As a graduate student, Michael developed the world's first GPS-based precision steering system for farm vehicles. He went on to bring this technology to market with Novariant and helped launch the precision agriculture industry.

ABSTRACT

This paper describes the latest innovations and experimental results for assured time and location based on Low Earth Orbit (LEO) satellites.

Interest is growing worldwide to identify additional sources of PNT to augment existing GNSS sources. Industry and government groups are actively seeking independent timing solutions to ensure uninterrupted operation of the critical infrastructure, including data centers, financial markets, cellular networks, and power distribution. Military users are also interested in robust and reliable geolocation capabilities, even in environments where GPS or GNSS is not available. Commercial and academic entities serving these industries are actively exploring a wide range of technologies to support a comprehensive solution for assured PNT.

Results from three separate user equipment configurations are presented – each of which is intended to increase the real-time performance of the Satellite Time and Location (STL) system, a non-GNSS solution for assured time and location that is highly resilient and physically secure. STL uses the Iridium constellation of 66 communications satellites in Low Earth Orbit (LEO) to transmit specially structured time and location broadcasts. Due to their high RF power and signal coding gain, the STL broadcasts are able to penetrate into difficult attenuation environments, including deep indoors. Like GNSS signals, these broadcasts are specifically designed to allow a receiver to obtain precise time and frequency measurements to derive its position, navigation, and time (PNT). STL is able to augment or serve as a back-up to existing GNSS PNT solutions by providing secure measurements in the presence of high attenuation (deep indoors), active jamming, and/or malicious spoofing.

The first configuration substituted a rubidium clock (a very stable frequency source based on atomic physics rather than quartz crystals) for the Temperature Compensated Crystal Oscillator (TCXO) used as the STL receiver's timebase during earlier experiments. Using the rubidium clock, the STL receiver demonstrated a Maximum Time Interval Error (MTIE) of 170 nanoseconds over a two-week period at a static location which was precisely known *a priori*.

The second configuration utilized the same hardware setup, with the receiver configured to a static location that was unknown, and with a rubidium clock that was still warming up 6 hours after a cold start. The demonstrated MTIE for this configuration was 420 nanoseconds over a seven-day period.

The third configuration utilized a nearby STL reference station to transmit localized error measurements to the STL ground segment. The reference receiver used a GPS-derived timebase that was assumed to be perfect. Timing results from 3 receivers, with different internal OCXO oscillators, are presented.

INTRODUCTION

The Iridium constellation consists of 66 Low Earth Orbiting (LEO) satellites primarily used to communicate with mobile users across the globe. Both the satellites and mobile users transmit signals in the L-Band at carrier frequencies between 1616 and 1626 MHz, using Quadrature Phase Shift Keying (QPSK) with a symbol rate of 25,000 symbols per second. The satellites and mobile users take turns transmitting on the same set of frequencies during different parts of one signal frame, which lasts 90 milliseconds.

Iridium satellites travel at speeds of about 7500 m/s relative to the ground, resulting in apparent variations of up to +/− 36 kHz from the nominal carrier frequency due to Doppler effects. Compared to GNSS signals, Iridium signals have much higher raw signal power (300 ~ 2400x) as seen by a receiver on Earth, making them attractive for use in location applications where GNSS is obstructed, for example deep indoors.

Unlike GNSS satellites, Iridium satellites use spot beams to focus many distinct transmissions on separate, relatively small geographic areas. Each satellite supports 48 spot beams. The Iridium system's complex, overlapping spot beams enable a unique mechanism to provide location based authentication which alone is extremely difficult to spoof. Additionally, the fast LEO orbits of Iridium generate Doppler signatures significantly stronger than GPS which increases the utility of the STL signal for positioning applications.

SATELLITE TIME AND LOCATION (STL)

Although primarily designed for voice communications, the Iridium system supports the equivalent of common "text messages" which can be transmitted during a single 90 ms signal frame. Satelles uses this capability to transmit single-frame messages ("bursts") specifically designed for PNT applications. The STL burst appears to the Iridium satellite as a simple text message but is actually a carefully formatted set of data which produces a spread-spectrum RF signal pulse from the satellite's transmitter. The proprietary STL burst contains a pilot channel and a data channel, both highly encoded, enabling the receiver to apply a significant amount of coding gain to recover even weak signals which penetrate deep indoors.

The coding gain is so effective that an STL receiver can make precise time (pseudorange) and frequency measurements of each burst at attenuations of up to 39 dB relative to unobstructed reception. This is sufficient to penetrate buildings and other occlusions, providing coverage in most deep-indoor and urban-canyon environments. The receiver can use these measurements for a number of purposes, including 1) aiding GNSS acquisition, 2) augmenting GNSS measurements when not enough GNSS satellites are in view, 3) computing position fixes directly, independent of GNSS, or 4) transferring sub-microsecond timing to a user or device.

In environments where both GNSS and STL time and location fixes are possible, the GNSS fixes will generally be more accurate. One key advantage of STL is its ability to provide time and position fixes under conditions where GNSS is not available due to occlusions, spoofing, or other issues. In this respect, GNSS and STL can be seen as complementary technologies, and it is apparent that receivers supporting both are highly desirable when practical.

Another key advantage of STL is the receiver's ability to confirm that it is not being spoofed. The proprietary STL signal format includes cryptographically secure features which unambiguously demonstrate that a signal burst was received directly from a satellite, rather than being synthesized or delayed and rebroadcast by an attacker. These cryptographic features also allow the receiver to prove its current location to a third party. This location-based authentication provides an independent confirmation of the identity of a remote system or user [1].

STL RECEIVER

The experiments described here were performed with the Satelles EVK2 receiver, a flexible evaluation kit used to demonstrate many STL features and applications. The authors previously [2] described timing results taken from an earlier version EVK1 receiver which was based on a Temperature Compensated Crystal Oscillator (TCXO). It subsequently became clear that improved timing results would be desirable. The EVK2 uses an internal 20 MHz frequency reference which can be chosen from among several models of Temperature Compensated Crystal Oscillators (TCXO) and Oven-Controlled Crystal Oscillators (OCXO) when the receiver is manufactured. There is also an option to substitute an external 20 MHz or 10 MHz frequency reference input. This option was used for the rubidium clock experiments described here.

TIMING REFERENCE

The goal of these experiments was to generate a pulse per second (PPS) output aligned as closely as possible with the beginning of the civil second, as defined (in the United States) by the US Naval Observatory (USNO). The experiments were conducted in California, far from the USNO in Maryland, so a locally available source of accurate civil seconds was needed. Traditionally, this is obtained from a timing receiver which observes the GPS satellites. The timing of the GPS satellite constellation has been shown to be aligned to the USNO second within 5 to 10 ns over the long term. However, the PPS output of any given GPS timing receiver may be 40 to 100 ns different from the GPS constellation time, depending on well-known GPS error sources such as ionospheric and tropospheric propagation, satellite visibility, multipath, etc.

For the experiments, PPS pulses from Trimble Thunderbolt receivers were used as a timing reference. These receivers were manufactured circa 2004, but their design goes back to the late 1990's, when Selective Availability was still active and WAAS signals were not yet available. These receivers are specified to provide a PPS pulse within 40 ns of USNO under good conditions. This should be considered as an error source in the measurements reported here, although we believe that the Thunderbolt receivers performed better than their specifications during these tests.

RUBIDIUM CLOCK EXPERIMENTS

For the rubidium clock experiments, the external frequency reference input of the Satelles EVK2 receiver was driven by the 10 MHz output of a Stanford Research Systems (SRS) rubidium vapor frequency reference, either the PRS10 module or the FRS725 laboratory instrument based on the PRS10 module (Figure 1). The time-related specifications of the two units are identical. The EVK2's internal filter parameters related to timing performance were adjusted to reflect the improved specifications of the rubidium frequency reference over the previous OCXO and TCXO references.

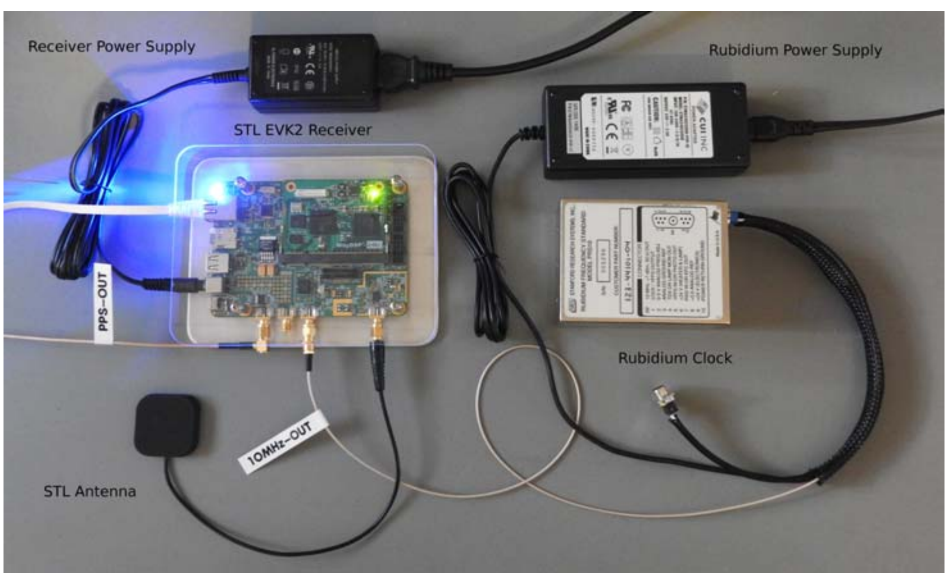

Figure 1: Rubidium Oscillator Experimental Setup

RUBIDIUM OUTDOOR ANTENNA TEST

It is well-known that the stability of most frequency references improves with the length of time the reference has been in continuous normal operation. The first experiment used a PRS10 rubidium frequency reference which had been continuously powered for several months, to illustrate the system performance that might be obtained in a permanent installation such as a data center. For this first experiment, the EVK2 was connected to an Iridium antenna sited on a rooftop with excellent visibility in all directions. The position of this antenna was known within 30 cm, and this static position was entered into the EVK2.

The PPS reference for this experiment was a Thunderbolt connected to a survey-grade choke ring antenna in a near-optimum rooftop location. That particular Thunderbolt also has an unusually good internal OCXO, and its internal parameters have been especially tuned for excellent PPS performance. Comparison with other instruments indicates that its short-term (up to 1000 s) timing variations are on the order of 10 ns.

The current implementation of the EVK2 timing filters requires about 6 hours to converge to the desired level of accuracy. Accordingly, the first six hours of data from this experiment were ignored, and the following 14 days were analyzed. The raw results are shown in Figure 2 below. The Maximum Time Interval Error (MTIE, a peak-to-peak error measurement) over the entire run was 170 ns. The mean error (bias) for the entire run was −11 ns, and the standard deviation was 30 ns. It is clear from the figure that the error is not stationary (i.e. the mean value depends on the interval measured), and in any case the mean is adjustable via a “cable delay” parameter used to compensate for the electrical length of the antenna cable.

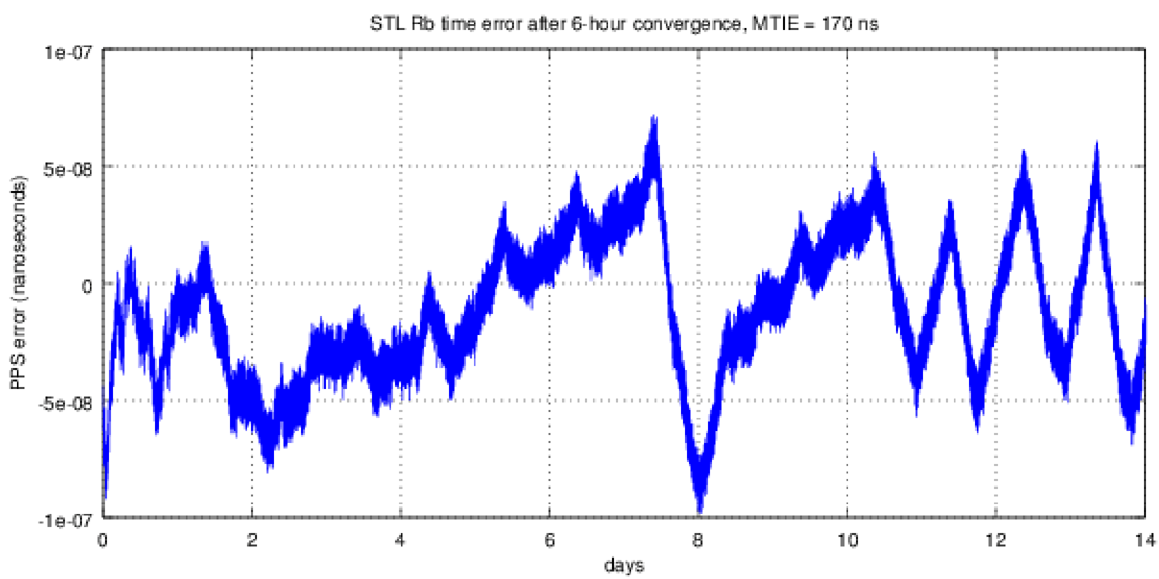

Figure 2: Timing Results with Rubidium Timebase – Outdoor, Optimal Configuration

RUBIDIUM INDOOR ANTENNA TEST

The second rubidium oscillator experiment showed the performance which could be expected from the system in an indoor, non-surveyed, or temporary installation. The STL antenna for this test was a small patch antenna mounted atop the STL receiver, in an indoor office environment. The receiver was given an initial guess location within 5 km of the actual location, but the receiver was expected to navigate itself to discover its true location as well as discovering the actual time. The rubidium frequency reference and the STL receiver were switched on almost simultaneously.

In the lab used for this experiment, the Thunderbolt's GPS antenna cannot be sited well due to property management concerns. Its view of the sky is partially obscured, and it appears to be subject to severe multipath. The Thunderbolt was observed to wander as much as 40 ns over a few tens of seconds. This is a sizeable fraction of the STL errors anticipated for this experiment. To improve the accuracy of the timing reference, the Thunderbolt PPS pulse was smoothed using a rubidium-based SRS FS725 frequency and time reference, with a time constant of about 2.5 hours. This appeared to decrease the timing errors to the 10 ns level, although no independent check was available.

This test was intended to investigate the accuracy available as soon as the receiver was switched on. At this point, the receiver does not know its true position or time as well as it will after its filter converges. Furthermore, the rubidium clock itself exhibits frequency drift (aging), which the receiver must estimate and remove, and this aging decreases exponentially over time. For these reasons, we expect that the timing accuracy will improve with time, up to a point; this is why the previous test was given six hours to converge. In this test, the MTIE for the whole run (more than 12 days) was 656 ns (Figure 3). The MTIE starting six hours after power-on was 420 ns. The mean was −141 ns and the standard deviation was 107 ns. In the first experiment, which showed better results, the rubidium clock had been continuously powered for months, so that its aging was negligible. In this experiment, the rubidium clock was still aging rapidly through the duration of the experiment due to the definition of this scenario.

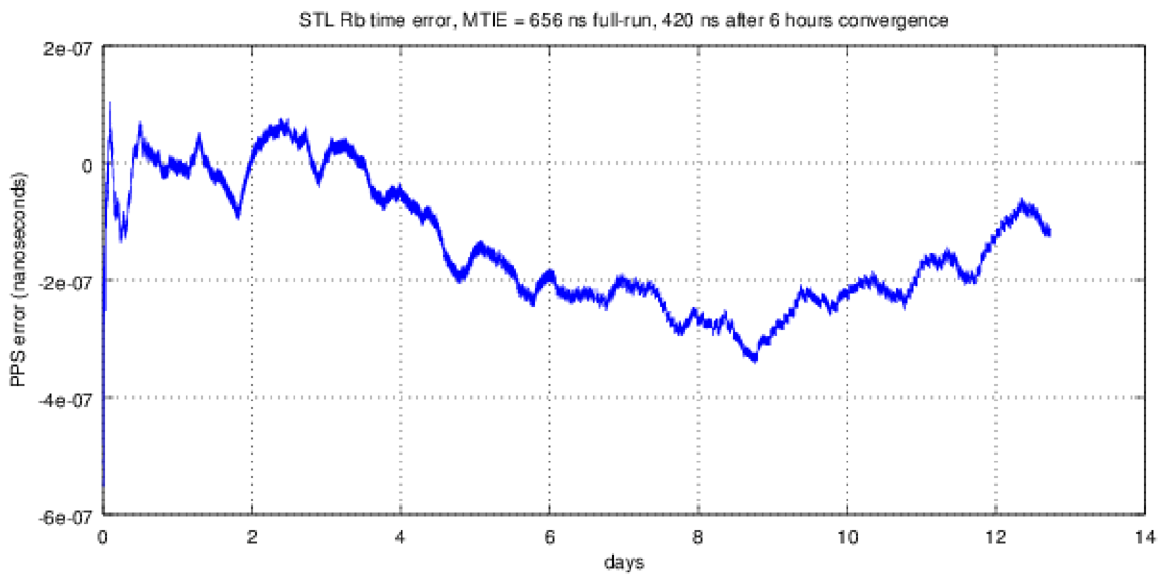

Figure 3: Timing Results with Rubidium Timebase – Indoor, Sub-optimal Configuration

STL "BASE STATION" AIDED DATA COLLECTION

The third experiment was designed to investigate the impact of simple, network-based differential corrections on STL timing. As with GPS signals, the presence of a local STL differential correction source is expected to reduce the effects of satellite ephemeris errors, satellite clock errors, and ionospheric and tropospheric errors on the STL navigation and timing results. This concept was tested over a baseline of approximately 20 km.

Data was collected on three (3) STL EVK2 receivers simultaneously, each with a slightly different version of on-board OCXO timing reference. To help mitigate the impact of any short-term error sources, such as specific satellites, time-of-day effects, multipath effects, and others, data was collected for 10 days without a local reference station, and for 10 days with a local reference station. The timing output of the STL receiver was compared to the timing output of the rubidium-disciplined Thunderbolt receiver described above. The results are shown in Table 1 below.

Receiver	No Base Station			With Base Station		
	Mean	1-σ	MTIE	Mean	1-σ	MTIE
EVK2-023 (OCXO v3)	16	62	441	-12	44	323
EVK2-028 (OCXO v2)	23	83	657	-3	66	565
EVK2-027 (OCXO v1)	31	97	715	4	90	600

Table 1: Timing Offset from GPS (in nanoseconds) – 10-day Trials

As shown in the table, providing differential corrections from a local base station improved all timing performance metrics for each receiver. These improvement were not dramatic, but the benefits provided by the differential corrections is reasonably consistent across multiple receivers.

Detailed timing results for EVK2-023, with and without the local reference station corrections, are shown in Figure 4 and Figure 5 below.

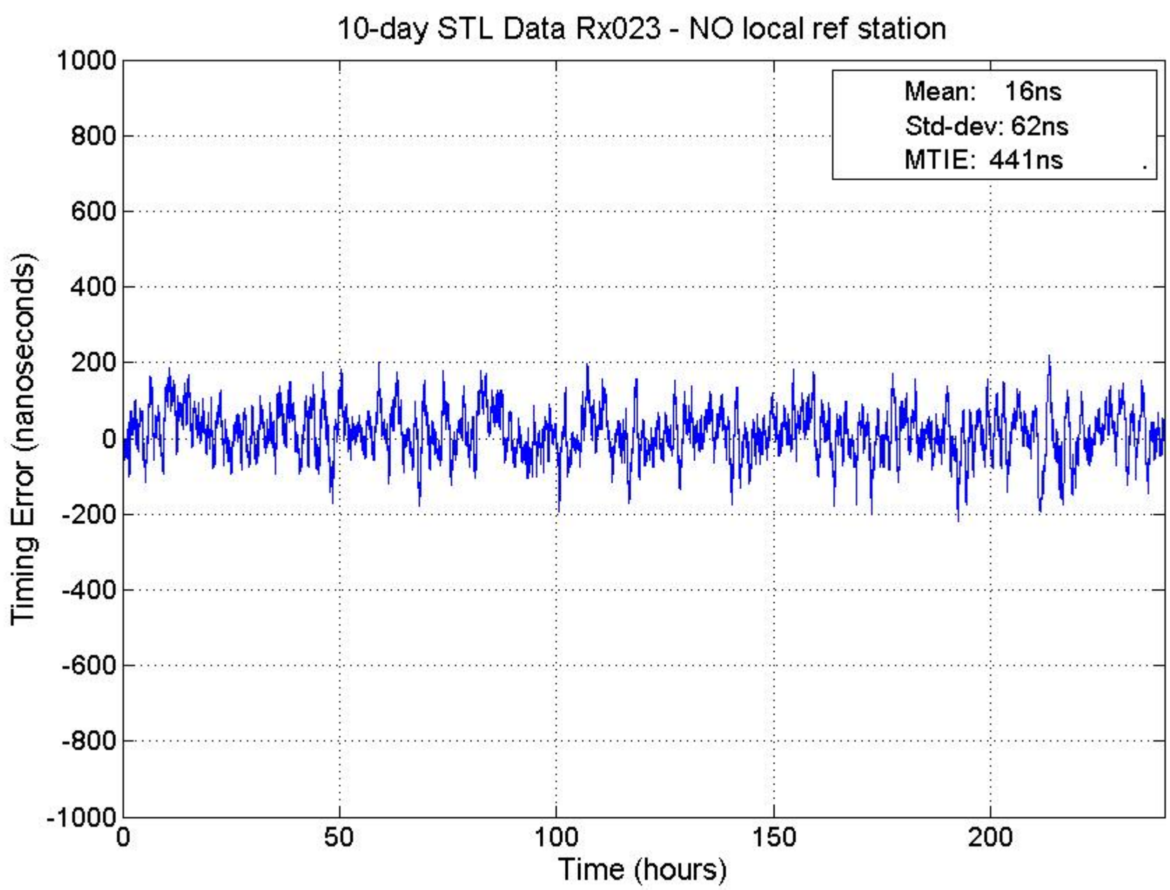

Figure 4: Timing Results with OCXO Timebase <u>Without</u> Differential Corrections

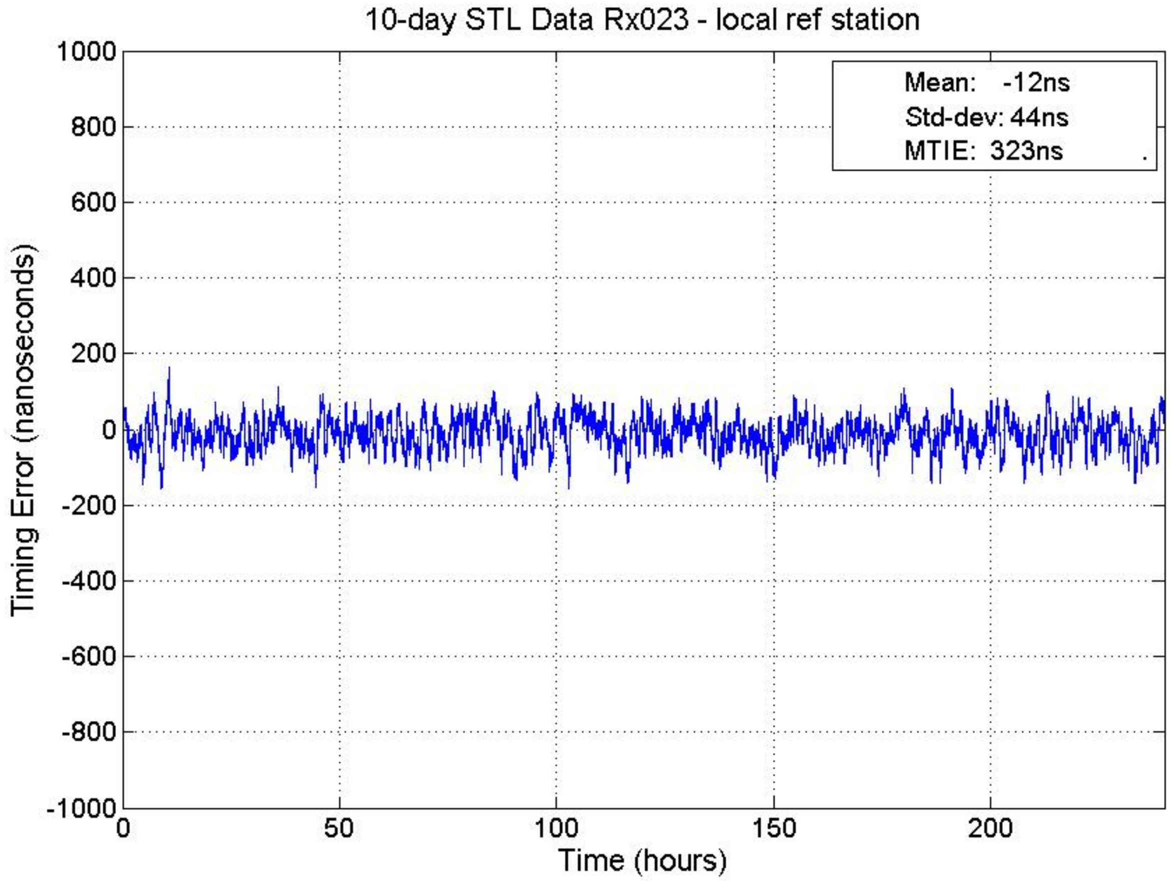

Figure 5: Timing Results with OCXO Timebase With Differential Corrections

CONCLUSIONS

LEO-based signals can deliver a time and location solution into environments where GNSS signals are not available – thereby augmenting GNSS solutions and improving availability and robustness.

In previous research, sub-microsecond timing accuracy was demonstrated using a TCXO disciplined to Satellite Time and Location (STL) – a LEO-based solution delivered over the Iridium satellite constellation. While sub-microsecond timing is sufficient for many applications, higher timing accuracy is desired by some users. In this work, the authors expanded on previous research to improve the timing accuracy performance of STL-based solutions.

For a stand-alone (non-differential) configuration, it was demonstrated that sub-500-nanosecond MTIE and order-100-ns standard deviation is achievable for a rubidium-based STL receiver with an unknown static location and low-performance indoor antenna. When the receiver is in a known location with an outdoor antenna, timing MTIE improves to 170ns, and standard deviation improves to 30 nanoseconds.

Differential performance with a lower-cost OCXO oscillator was also explored. Without differential corrections applied in the STL ground segment, standard deviations in the range of 62-97 ns were achieved, with MTIE in the range of 441 to 715 ns over 10 day trials. When differential corrections were applies, the range of standard deviations improved to 44-90 ns, and the range of MTIE values improved to 323-600 ns.

This research demonstrates that the application of STL for GNSS augmentation is not limited to microsecond-level applications. Performance levels of sub-100 nanoseconds are achievable using differential techniques or by leveraging higher precision reference oscillators.

REFERENCES

[1] J. Cookman, G. Gutt, D. Lawrence. “Single chip receiver for GNSS and LEO constellations.” Proceedings of the Institute of Navigation 2013 GNSS Conference, Nashville, TN, September 2013.

[2] D. Lawrence, H. S. Cobb, G. Gutt, F. Tremblay, P. Laplante, M. O’Connor. “Test Results from a LEO-Satellite-Based Assured Time and Location Solution.” Proceedings of the Institute of Navigation 2016 National Technical Meeting, Monterey, CA, January 2016.